08-08-00

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PATENT APPLICATION TRANSMITTAL LETTER	Docket Number 410

JC867 U.S. PTO 08/07/00

JC760 U.S. PTO 09/633598 08/07/00

TO THE COMMISSIONER OF PATENTS AND TRADEMARKS:

Transmitted herewith for filing is the patent application of:

For:
Enclosed are:

[x] 2 sheet(s) of drawing(s) Figures 1-3

[x] Assignment of the invention to Advanced Technology Materials Inc.

[ ] A certified copy of a ______________________ application.

[x] Declaration and power of attorney.

[x] Specification, claims, and abstract.

[ ] A verified statement to establish small entity status under 37 CFR 1.9 and 37 CFR 1.27.

CLAIMS AS FILED:

	Column 1	Column 2	Small Entity			Other Than a Small Entity	
FOR:	NO. FILED	NO. EXTRA	RATE	FEE	OR	RATE	FEE
BASIC FEE					OR		$690.00
TOTAL CLAIMS	10- 20 =	0	0 x $9 =		OR	x $18 =	
INDEP. CLAIMS	2- 3 =	0	0 x $39 =		OR	x $78 =	
[ ] MULTIPLE DEPENDENT CLAIM PRESENTED			+ $130 =		OR	+ $260 =	
			Total			Total	$690.00
Fee for recording the assignment=						1 x 40 =	40.00
Amount of check=							$730.00

* If the difference in Column 1 is less than zero, Enter "0" in Column 2.

[x] A check is enclosed in the amount of $730.00 to cover the filing fee and the fees for recording the assignments.

[x] The Commissioner is hereby authorized to charge and credit any deficiency or excess to Deposit Account No. 50-0860. A duplicate copy of this sheet is enclosed.

"Express Mail" mailing label number: EL604222724US
Date of Deposit: August 7, 2000

I hereby certify that this new patent application with filing fee is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to BOX PATENT APPLICATION, Assistant Commissioner for Patents, Washington, DC 20231.

Lee Ann DiLello
(Typed or printed name of person mailing paper or fee)

Lee Ann DiLello
(Signature of person mailing paper or fee)

August 7, 2000
Date

Oliver A. Zitzmann
Registration Number 38,691

00/40/80 - 09633598 - 080700

2771-410

UNITED STATES PATENT APPLICATION

OF

JOAN M. REDWING

EDWIN L. PINER

FOR

INDIUM GALLIUM NITRIDE CHANNEL HIGH ELECTRON MOBILITY TRANSISTORS, AND METHOD OF MAKING THE SAME

GOVERNMENT RIGHTS IN INVENTION

The invention was made in the performance of the U.S. Army Space and Missile Defense Command, Contract Number DASG60-98-C-0025. The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

Field Of The Invention

This invention relates to high electron mobility transistor (HEMT) devices and method of making the same.

Description of the Related Art

GaN based materials have physical and electronic properties that make them attractive for high temperature, high power and high frequency devices. Wide bandgap semiconductors (GaN and SiC) have inherently lower thermal carrier generation rates and higher breakdown fields compared to Si and GaAs, as shown in Table 1 below.

Table 1

Properties of candidate materials for high power, high temperature, high frequency electronic devices

Material Property	Si	GaAs	4H-SiC	GaN
Bandgap (eV)	1.1	1.4	3.3	3.4
Breakdown field (10^5 V/cm)	2	4	30	30?
Electron mobility (cm^2/Vs)	1400	8500	800	900^a,2000^b
Maximum velocity (10^7 cm/s)	1	2	2	3
Thermal conductivity (W/cm K)	1.5	0.5	4.9	1.3

(a) for n = 5E16 cm^{-3}; (b) for an AlGaN/GaN structure

GaN has additional advantages including a high (> 800 cm^2/Vs) electron mobility and a high (> 10^7 cm/sec) electron velocity. Furthermore, high electron mobility transistors (HEMTs) which offer higher mobilities, better charge confinement and higher breakdown voltages can be fabricated in the AlGaN/GaN materials system. Room temperature radio frequency (8-10 GHz) output powers on the order of 6-8 W/mm are theoretically possible in the AlGaN/GaN materials system and power densities as high as 6.8 W/mm have recently been reported (S.T. Sheppard, et al., 56th Device Research Conference, Charlottesville, VA, June 22-24, 1998).

While promising output powers have been reported in AlGaN/GaN HEMTs, materials-related issues continue to limit device performance. Persistent photoconductivity (PPC) and drain I-V collapse have been reported in AlGaN alloys (M.D. McCluskey, N.M. Johnson, C.G Van De Walle, D.P. Bour, M. Kneissl and W. Walukiewicz, *Mat. Res. Soc. Symp. Proc.* 521 (1998), p. 531) and AlGaN/GaN heterostructures (J.Z. Li, J.Y. Lin, H.X. Jiang, M. A. Khan and Q. Chen, *J. Appl. Phys.* 82 (1997) 1227). These effects arise from carrier trapping and generation from deep levels in the material and can lead to poor high frequency performance, decreased drain currents and reduced output powers in a HEMT. PPC and current collapse in GaAs-based HEMTs have been attributed to defect-donor complexes (DX centers) in $Al_xGa_{1-x}As$ when x>0.20. Evidence for oxygen DX-centers in Al-rich $Al_xGa_{1-x}N$ (x>0.27) has recently been reported (M.D. McCluskey, et al., *ibid.*). High Al content AlGaN layers (x>0.20) are commonly used to achieve high sheet densities in AlGaN/GaN HEMT structures via piezoelectric-induced doping as shown by

the data in Figure 1, which is a plot of sheet density as a function of percent aluminum composition in undoped 23 nanometer AlGaN/GaN heterostructures.

In order to further improve the performance of III-V nitride HEMTs, methods must be identified to reduce or eliminate the deleterious effects of deep level defects that result from the use of high Al composition layers.

SUMMARY OF THE INVENTION

The present invention relates in one aspect thereof to a gallium nitride-based HEMT device, comprising a channel layer formed of an InGaN alloy.

Such device may comprise an AlGaN/InGaN heterostructure, e.g., in a structure including a GaN layer, an InGaN layer over the GaN layer, and an AlGaN layer over the InGaN layer. The AlGaN layer may be doped or undoped, as necessary or desired in a given end use application of the HEMT.

Alternatively, the HEMT device of the invention may be fabricated as a device which does not comprise any aluminum-containing layer, e.g., a GaN/InGaN HEMT device or an InGaN/InGaN HEMT device.

In another aspect, the invention relates to a method of fabricating a GaN-based HEMT device, comprising forming a channel layer for the device of an InGaN alloy.

Other aspects, features and embodiments of the invention will be more fully apparent from the ensuing disclosure and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a plot of sheet density versus % Al in undoped 23 nm AlGaN/GaN heterostructures, showing that piezoelectric-induced doping results in an increase in sheet density with increasing Al composition.

Figure 2 is a schematic representation of an AlGaN/InGaN HEMT structure.

Figure 3 is a band diagram of an AlGaN/InGaN HEMT structure.

DETAILED DESCRIPTION OF THE INVENTION, AND PREFERRED EMBODIMENTS THEREOF

In accordance with the present invention, the performance of GaN-based HEMTs is improved by use of InGaN alloys in the channel layer of the device.

The use of InGaN alloys in the channel layer of HEMT devices has been discovered to permit substantially lower Al composition AlGaN layers to be employed at equivalent levels of strain and piezoelectric doping characteristic of AlGaN/GaN heterostructures.

InGaN provides a large a-lattice constant in relation to GaN (the a-lattice constant difference between GaN and InN is 0.351Å, compared to a 0.079Å difference between GaN and AlN), and low Al and In content layers can be used to produce pseudomorphic AlGaN/InGaN heterostructures with comparable strain to AlGaN/GaN. For example, the

lattice mismatch of an $Al_{0.10}Ga_{0.90}N/In_{0.046}Ga_{0.954}N$ interface is identical to that of $Al_{0.30}Ga_{0.70}N/GaN$. Consequently, it is possible to produce AlGaN/InGaN heterostructures that enable the use of reduced Al content AlGaN layers without significant reductions in piezoelectric-induced doping or degradation of the structural or electrical properties of the channel layer.

In addition to a reduction in DX-center related transient effects, the use of low Al content AlGaN layers in the HEMT enables reduced ohmic contact resistance to be achieved.

The high electron mobility of InN (4000 cm^2/Vs for n=1E16 cm^{-3}) in relation to GaN permits the use of InGaN alloys in the channel layer of the device to significant improvements in electrical properties and device performance.

Figure 2 is a schematic representation of an AlGaN/InGaN HEMT structure for an illustrative device according to the present invention. In the fabrication of this device, a pseudomorphic AlGaN layer is grown on top of an InGaN layer overlying a GaN layer, using appropriate growth conditions readily determinable without undue experimentation by those of ordinary skill in the art. The InGaN layer should be thick enough so that it is "relaxed" in the multilayer structure. Typical thicknesses in various embodiments of the invention may include thicknesses of the InGaN layer in the range of from about 100 to about 5,000 nanometers, with more specific thicknesses in some instances being in the range of from about 200 to about 2,000 nanometers, or in a narrower range of from about 400 to about 1,000 nanometers.

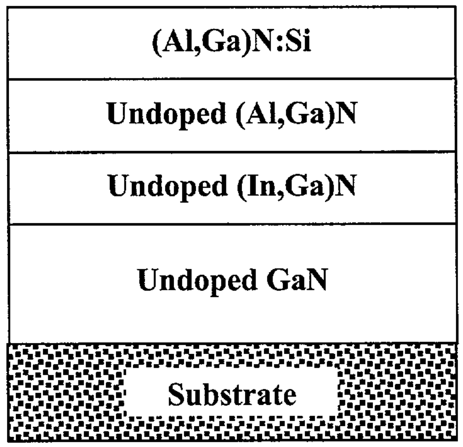
Alternatively, the InGaN layer can be grown directly on the substrate (including a buffer layer). The AlGaN layer can be undoped or the upper or top-most portion of the AlGaN can be doped to further increase the sheet density.

Alternatively, an InGaN channel HEMT can be fabricated using GaN or InGaN on InGaN. In this case, chemically reactive Al-containing layers are completely eliminated from the device structure, to provide a GaN/InGaN HEMT with improved long-term stability and reliability characteristics under high power operation than are achievable by an AlGaN/GaN HEMT or an AlGaN/InGaN HEMT. Additionally, an InGaN/InGaN HEMT provides fabricational advantages due to the differing optimum growth conditions between InGaN, and AlGaN or GaN.

The growth of the indium gallium nitride layers in the practice of the invention may be effected by any suitable process or technique therefor. For example, such layers may be formed by vapor phase techniques in which reactant gas species (e.g., ammonia, trimethylgallium, and trimethylindium) enter a growth reactor that contains the substrate. The reactant gas species passes over the substrate depositing an epitaxial film of said species (i.e., nitrogen from ammonia, gallium from trimethylgallium, and indium from trimethylindium). The InGaN process may occur at temperatures in the range of from about 500 to 1000°C, with a more specific temperature range of from aobut 700 to 950°C, or in a narrower temperature range of from about 800 to 900°C. The pressure of the reactor may be maintained in the range of from about 50 to 980mbarr. The indium-to-gallium ratio may be anywhere in the range of from 0 to 100%.

The features, aspects and advantages of the present invention are further shown with reference to the following non-limiting examples relating to the invention.

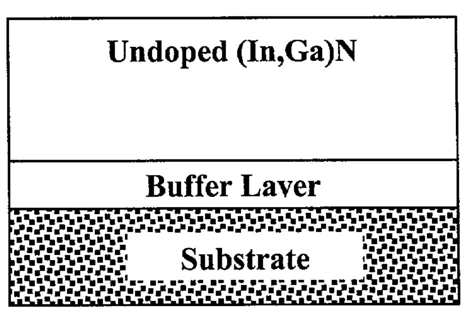
EXAMPLE 1



Example of the fabrication of an HEMT structure of the type shown in Figure 2

A HEMT structure of the design shown in Example 1 comprises a suitable substrate for depositing GaN; an unintentionally doped GaN layer as a buffer over said substrate; an unintentionally doped InGaN channel layer over said GaN buffer layer that is relaxed with respect to strain due to the different lattice constants of the said GaN buffer layer and the InGaN channel layer; an unintentionally doped AlGaN spacer layer over said InGaN channel layer; an intentionally silicon-doped AlGaN donor layer over said AlGaN spacer layer.

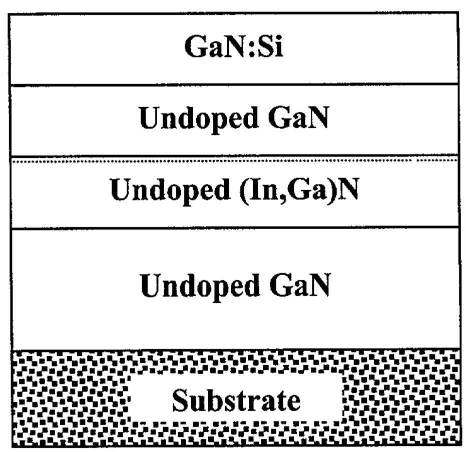
EXAMPLE 2



Example of the fabrication of the InGaN layer being formed directly on a substrate, with a buffer layer

An InGaN structure of the design shown in Example 2 comprises a suitable substrate for depositing GaN; a buffer layer over said substrate; an unintentionally doped InGaN layer over said buffer layer.

EXAMPLE 3

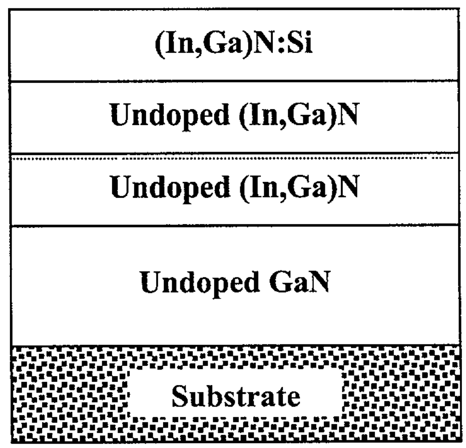


Example of the fabrication of a GaN/InGaN HEMT device

A HEMT structure of the design shown in Example 3 comprises a suitable substrate for depositing GaN; an unintentionally doped GaN layer as a buffer over said substrate; an unintentionally doped InGaN channel layer over said GaN buffer layer that is relaxed with respect to strain due to the different lattice constants of the said GaN buffer layer and the InGaN channel layer; an unintentionally doped GaN spacer layer over said

InGaN channel layer; an intentionally silicon-doped GaN donor layer over said AlGaN spacer layer.

EXAMPLE 4



Example of the fabrication of an InGaN/InGaN HEMT device

A HEMT structure of the design shown in Example 4 comprises a suitable substrate for depositing GaN; an unintentionally doped GaN layer as a buffer over said substrate; an unintentionally doped InGaN channel layer over said GaN buffer layer that is relaxed with respect to strain due to the different lattice constants of the said GaN buffer layer and the InGaN channel layer; an unintentionally doped InGaN spacer layer that has a lower InN concentration compared to the InGaN channel layer over said InGaN channel layer; an intentionally silicon-doped InGaN donor layer over said InGaN spacer layer that has the same InN concentration as the InGaN spacer layer. In this example, the channel comprising the high density of charged carriers is formed at or near the interface between the InGaN channel layer and InGaN spacer layer due to the piezoelectric-induced doping as a result of the strain associated with the differing InN concentrations of the InGaN channel layer and InGaN spacer layer.

Although the invention has been variously disclosed herein with reference to illustrative embodiments and features, it will be appreciated that the embodiments and features described hereinabove are not intended to limit the invention, and that other variations, modifications and other embodiments will suggest themselves to those of ordinary skill in the art. The invention therefore is to be broadly construed, consistent with the claims hereafter set forth.

THE CLAIMS

What Is Claimed Is:

1. A gallium nitride-based HEMT device, comprising a channel layer formed of an InGaN alloy.

2. The device of claim 1, comprising an AlGaN/InGaN heterostructure.

3. The device of claim 1, comprising a GaN layer, an InGaN layer over the GaN layer, and an AlGaN layer over the InGaN layer.

4. The device of claim 1, which does not comprise an aluminum-containing layer.

5. The device of claim 4, comprising a GaN/InGaN HEMT.

6. The device of claim 4, comprising an InGaN/InGaN HEMT.

7. The device of claim 1, comprising an AlGaN layer.

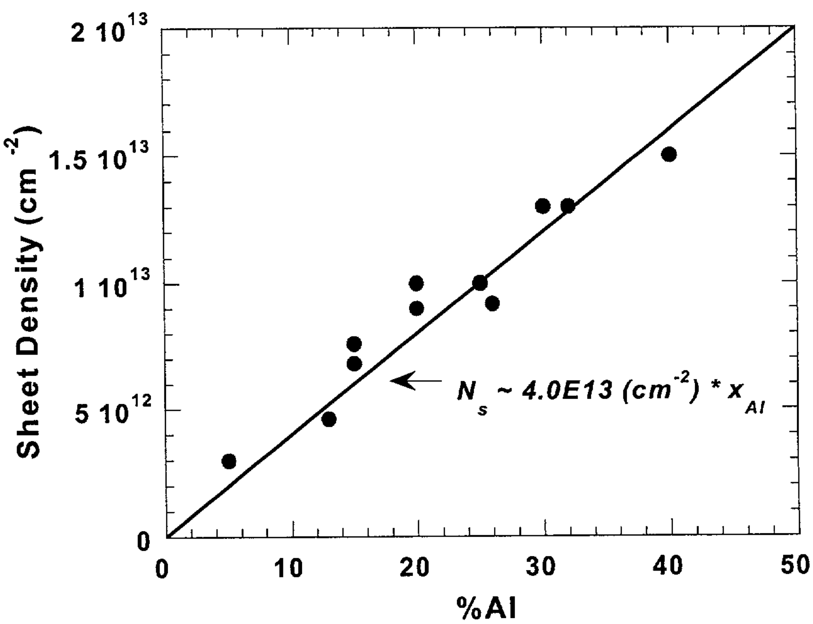
8. The device of claim 7, wherein the AlGaN layer is undoped.

9. The device of claim 7, wherein the AlGaN layer is doped with a dopant increasing the sheet density thereof.

10. A method of fabricating a GaN-based HEMT device, comprising forming a channel layer for said device of an InGaN alloy.

ABSTRACT OF THE DISCLOSURE

A gallium nitride-based HEMT device, comprising a channel layer formed of an InGaN alloy. Such device may comprise an AlGaN/InGaN heterostructure, e.g., in a structure including a GaN layer, an InGaN layer over the GaN layer, and a (doped or undoped) AlGaN layer over the InGaN layer. Alternatively, the HEMT device of the invention may be fabricated as a device which does not comprise any aluminum-containing layer, e.g., a GaN/InGaN HEMT device or an InGaN/InGaN HEMT device.



Sheet Density (cm^{-2})
$2\ 10^{13}$
$1.5\ 10^{13}$
$1\ 10^{13}$
$5\ 10^{12}$
0
0
10
20
30
40
50
%Al
$N_s \sim 4.0E13\ (cm^{-2}) * x_{Al}$

Figure 1

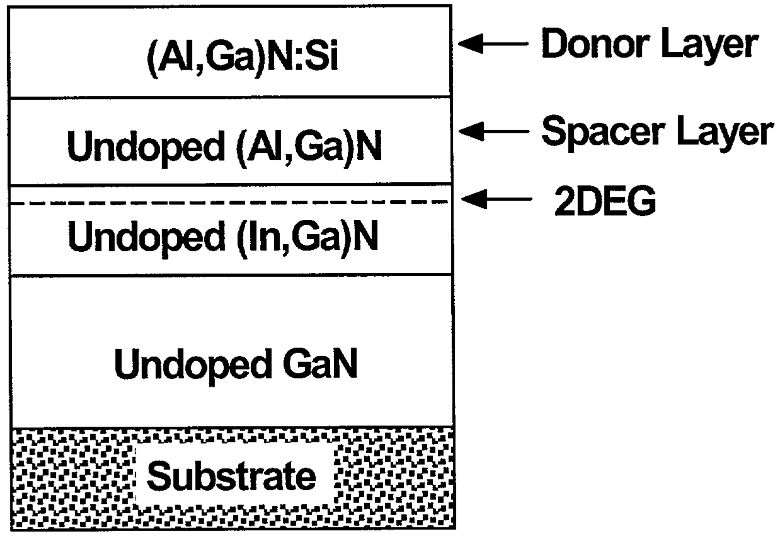


Figure 2

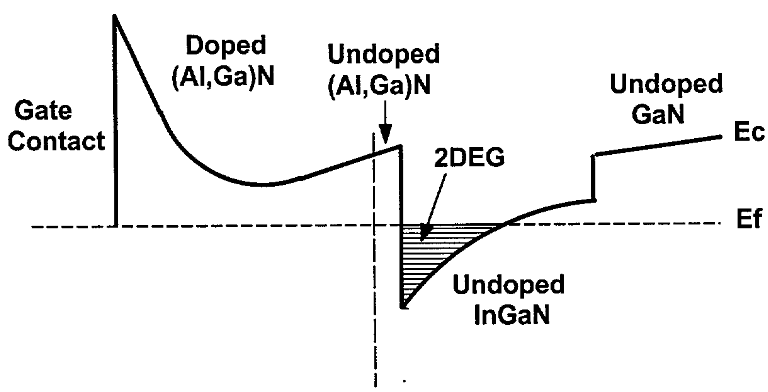


Figure 3

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

As a below-named inventor, **Joan M. Redwing and Edwin L. Piner**, do hereby declare that my residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled **"INDIUM GALLIUM NITRIDE CHANNEL HIGH ELECTRON MOBILITY TRANSISTORS, AND METHOD OF MAKING THE SAME"**, the specification of which

(check one) ☒ is attached hereto.
☐ was filed on ______________ as Application Serial No. ______________
☐ and was amended ________________________________(if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, §1.56(a).

I hereby claim foreign priority benefits under Title 35, United States Code, §119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)

(Number)	(Country)	(Day/Month/Year Filed)	Priority Claimed ☐ Yes ☒ No

I hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this specification is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, §112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, § 1.56(a) which occurred between the filing date of the prior application and the national or PCT international filing date of this application.

(Application Number)	(Filing Date)	(Status-Patented,Pending, abandoned)

I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements are made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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